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STUDY OF THE POLARIZATION OF LIGHT SCATTERED BY SEAWATER (ISSLE--ETC(U)
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STUDY OF THE POLARIZATION OF LIGHT SCATTERED BY SEAWATER

The state of a light beam is determined by the Stokes parameters, which will /136
be written as[1]

$$S_1 = I; \quad S_2 = IP\cos 2\Psi; \quad S_3 = IP\sin 2\Psi; \quad S_4 = Iq;$$

where I is the intensity (brightness) of the light beam; P is the degree of polarization of the light beam; Ψ is the angle of rotation of the direction of "maximum" polarization with respect to the plane of scattering; q is the degree of ellipticity.

An arbitrary partially polarized light beam of intensity I may be represented as the sum of two incoherent beams: a completely polarized beam of intensity I' = rI and a completely depolarized beam of intensity I" = (1 - r)I. The quantity $r = +\sqrt{P^2 + q}$ is the degree of homogeneity of the light beam.

The scattering matrix, which is a linear operator of the transformation of Stokes parameters for light scattering by a volume of seawater, was experimentally /13 determined with a laboratory matrix meter.

The first column of the scattering matrix represents the scattering volume of a turbid medium exposed to completely depolarized (natural) light with Stokes parameters

$$S_1 = I, \quad S_2 = S_3 = S_4 = 0,$$

The polarization parameters of the scattered light during exposure to natural light were obtained from the following formulas:

$$\left.\begin{aligned}
&P_* = +\sqrt{\tilde{f}_{21}^2 + \tilde{f}_{31}^2}; \\
&\Psi_* = \pm\left|\frac{1}{2}\operatorname{arctg}\left(\tilde{f}_{31}/\tilde{f}_{21}\right)\right| \text{ for } \tilde{f}_{21} > 0; \\
&\Psi_* = \pm\left[\frac{\pi}{2} - \left|\frac{1}{2}\operatorname{arctg}\frac{\tilde{f}_{31}}{\tilde{f}_{21}}\right|\right] \text{ for } \tilde{f}_{21} < 0; \\
&q_* = \tilde{f}_{41}; \\
&r_* = +\sqrt{\tilde{f}_{21}^2 + \tilde{f}_{31}^2 + \tilde{f}_{41}^2}.
\end{aligned}\right\} \quad (1)$$

In the formulas for Ψ_*, $\tilde{f}_{31} > 0$ has a (+) sign, and $\tilde{f}_{31} < 0$ has a (−) sign. If $\tilde{f}_{31} = 0$, then for $\tilde{f}_{21} > 0$, angle $\Psi_* = 0$, and when $\tilde{f}_{21} < 0$, angle $\Psi_* = \pi/2$. If $\tilde{f}_{21} = 0$, then for $\tilde{f}_{31} > 0$, angle $\Psi_* = +45°$, and when $\tilde{f}_{31} < 0$, angle $\Psi_* = -45°$.

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*Numbers in the right margin indicate pagination in the original text.

The second column of the scattering matrix represents the scattering volume of the turbid medium exposed to linearly polarized light beams: horizontally polarized $\{S_1 = S_2;\ S_3 = S_4 = 0\}$ and vertically polarized $\{S_1 = -S_2;\ S_3 = S_4 = 0\}$.

The third column of the scattering matrix represents the scattering volume exposed to linearly polarized light beams with polarization angles $\Psi = \pm 45\{S_1 = S_3;\ S_2 = S_4 = 0\}$, $\{S_1 = -S_3;\ S_2 = S_4 = 0\}$.

The fourth column of the scattering matrix represents the scattering volume exposed to light beams with circular polarization $\{S_1 = S_4;\ S_2 = S_3 = 0\}$, $\{S_\uparrow = -S_4;\ S_2 = S_3 = 0\}$.

The polarization parameters of the scattered light during exposure to completely alternatively polarized light beams were determined from the following formulas:

$$
\left.
\begin{aligned}
r_j^\pm &= \frac{\sqrt{(\tilde{f}_{21} \pm \tilde{f}_{2j})^2 + (\tilde{f}_{31} \pm \tilde{f}_{3j})^2}}{1 \pm \tilde{f}_{1j}}\ ; \\[6pt]
\Psi_j^\pm &= \pm \left| \frac{1}{2} \arctan\left(\frac{\tilde{f}_{31} \pm \tilde{f}_{3j}}{\tilde{f}_{21} \pm \tilde{f}_{2j}} \right) \right|, \text{for} \left(\tilde{f}_{21} \pm \tilde{f}_{2j}\right) > 0; \\[6pt]
\Psi_j^\pm &= \pm \left[\frac{\pi}{2} - \left| \frac{1}{2} \arctan\left(\frac{\tilde{f}_{31} \pm \tilde{f}_{3j}}{\tilde{f}_{21} \pm \tilde{f}_{2j}} \right) \right| \right] \text{for} \left(\tilde{f}_{2j} \pm \tilde{f}_{2j}\right) < 0; \\[6pt]
q_j^\pm &= \frac{\tilde{f}_{41} + \tilde{f}_{4j}}{1 \pm \tilde{f}_{1j}}\ ; \\[6pt]
r_j^\pm &= \pm \frac{\sqrt{(\tilde{f}_{21} \pm \tilde{f}_{2j})^2 + (\tilde{f}_{31} \pm \tilde{f}_{3j})^2 + (\tilde{f}_{41} \pm \tilde{f}_{4j})^2}}{1 \pm \tilde{f}_{1j}}\ .
\end{aligned}
\right\} \quad (2)
$$

The ($\pm$) signs of the polarization parameters correspond to the irradiating beams with $c\{\pm S_j\}$, where $j = 2, 3, 4$.

In the formulas for Ψ_j, $(\tilde{f}_{31} \pm \tilde{f}_{3j}) > 0$ has a (+) sign, and $(\tilde{f}_{31} \pm \tilde{f}_{3j}) < 0$ has a (−) sign. If $(\tilde{f}_{31} \pm \tilde{f}_{3j}) = 0$, then for $(\tilde{f}_{21} \pm \tilde{f}_{2j}) > 0$, angle $\Psi = 0$, and for $(\tilde{f}_{21} \pm \tilde{f}_{2j}) <$ $\Psi_j = \frac{\pi}{2}$. If $(\tilde{f}_{21} \pm \tilde{f}_{2j}) = 0$, then for $(\tilde{f}_{31} \pm \tilde{f}_{3j}) > 0$ angle $\Psi_j = +45°$, and for $(\tilde{f}_{31} \pm \tilde{f}_{3j}) < 0$, $\Psi_j = -45°$.

In Eqs. (1) and (2), $\tilde{f}_{ij}$ are the relative components of the scattering matrix.[1]

The experimentally obtained components of the scattering matrix of seawater have a smoother form than for monodisperse latex. The angular dependences of the components of the scattering matrix are more sensitive functions than the scattering indicatrices. Certain components of the scattering matrix, shown in Fig. 1, correspond to two samples of seawater with similar values of the scattering index. The samples were taken in the northeastern Black Sea in the summer of 1969, 1.5 miles from the shore at a depth of 10 m. The table shows data for membrane filtration, %.

The theoretical scattering indicatrix of spherical particles for a certain particle size distribution of the Young distribution type[2] is in good agreement with the experimental ones if one considers that scattering at angles greater than 15° is determined by particles with $\rho \leqslant 6$ and a refractive index $n = 1.15-1.20$. At smaller angles, the scattering is determined by particles with $\rho > 6$ and refractive index $n = 1.05$. Assuming the particles to be spherical, we find according to
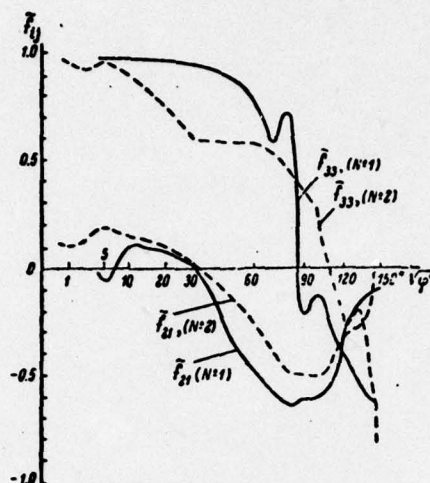
Fig. 1. Some relative components of the scattering matrix for samples Nos. 1 and 2

Number of sample, characteristics	Particle diameter, μm						Total number of particles, m³	Suspension, g/m³
	1–2.5	2.5–5	5–10	10–25	25–50	>50		
No. 1 $\sigma = 0.047$ m^{-1} $\varepsilon = 0.076$ m^{-1}	70.5	7.3	7.1	11.5	3.5	0.1	$873 \cdot 10^6$	0.62
No. 2 $\sigma = 0.051$ m^{-1} $\varepsilon = 0.09$ m^{-1}	71.0	8.4	7.6	10.5	2.0	0.5	$911 \cdot 10^6$	0.71

Shifrin[3] that the entire twice-refracted light is located within a cone with an apex angle of about 20° for n = 1.05. Since seawater contains up to 50-90% of fine particles not detectable by geologists, all the characteristics of the polarization curves at scattering angles greater than 15-20° depend on particles with $\rho \leqslant 6$, which in scattering theory correspond to the intermediate case between Rayleigh scattering and geometrical optics. At scattering angles up to 15-20°, the prin- /14 cipal polarization effects will be introduced by large particles with optical properties differing little from those of seawater.

Scattering of circularly polarized light (Figs. 2, 3, 4). To within a constant factor, the scattering matrix component $\tilde{f}_{14}$ is equal to the difference of scattered light intensities from clockwise-polarized light and from counterclockwise-polarized light. We see from the shape of the $\tilde{f}_{14}$ curve for sample No. 1 that the $\tilde{f}_{14}$ values are positive at angles of about 6°, although their magnitude is small. In the remaining angular interval, to within the experimental errors, $\tilde{f}_{14}$ may be taken to be equal to zero, with the exception of the angles 40-80°, where these values are negative (up to -0.2).
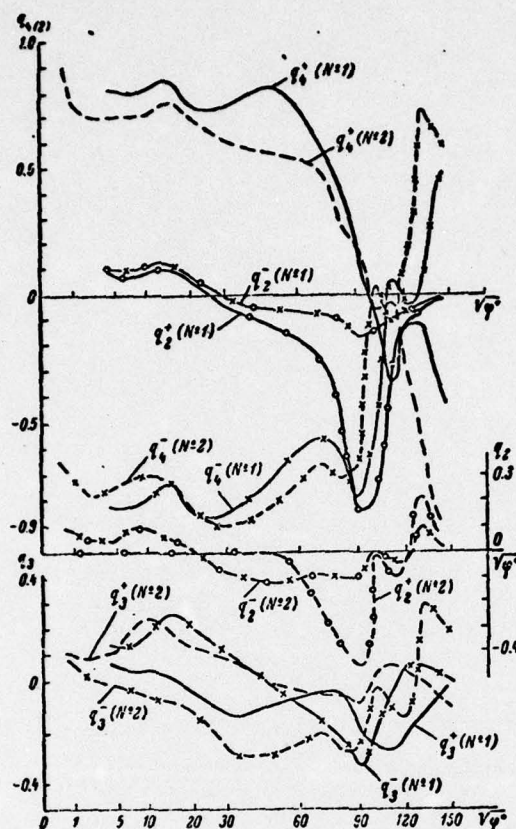
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Fig. 2. Ellipticity of scattered light from alternatively polarized irradiating
light beams.
(No. 1), (No. 2) - numbers of samples in all the figures.

For sample No. 2, the value of the component $\tilde{f}_{14}$ may always be assumed
to be zero, with the exception of the angles from 130°, where $\tilde{f}_{14}$ is negative.

The shapes of q_4 curves for the two samples are very similar, with a certain
shift of local maxima for sample No. 1 to larger scattering angles. No quantita-
tive characteristic of any kind appears possible. At a scattering angle of 100°,
the ellipticity disappears for both samples in the case of scattering of clockwise-
polarized light.

The dissimilarity of the behavior of $q_4^{\pm}$ curves in the 90° angle range may be
explained by the anisotropy of the optical properties of the material of the scat-
tering centers. A greater anisotropy is observed for sample No. 1.

Samples No. 1 and 2 differ very strongly in the behavior of the degree of linear
polarization $P_4^{\pm}(\phi)$. The greatest dissimilarity between $P_4^{\pm}$ and P_4^{-} is observed in
sample No. 2. For example, for the 70° angle, $R^{-} \sim 0$, and $R^{+} = 0.8$ is the maximum
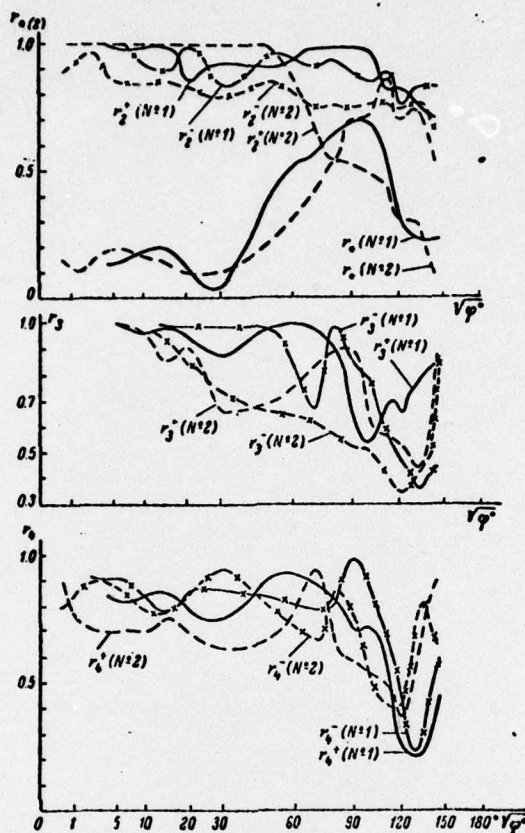value.

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Fig. 3. Degree of homogeneity of scattered light from alternatively polarized
irradiating light beams.

The depolarizing properties of the scattering volume determine the shape of the
$r_4(\phi)$ curve. The curves show a certain regularity. Since the r_4 curve represents
the polydispersity of the scattering volume, it may be concluded that sample No. 2
is more polydisperse, but the largest minimum is characteristic of sample No. 1 at
a scattering angle of 130°.

Scattering of alternatively polarized light beams with a polarization angle of
±45° (Figs. 2, 3, 5). To within a constant coefficient, the behavior of the scat-
tering matrix component $\tilde{f}_{13}$ is equal to the difference of the total intensities of
the scattered light beams from linearly polarized irradiating light beams with a   /144
polarization angle of ±45°. This value is rather insignificant for sample No. 1
and vanishingly small for sample No. 2.

The ellipticity for both samples never exceeds 0.35. Approximately the same
shape of q_3^+ and q_3^- curves is observed, as if with a parallel shift of one of the
curves relative to the other, and a slight deformation. The moderate values of q
over the entire range of scattering angles suggest that the material of the suspen-
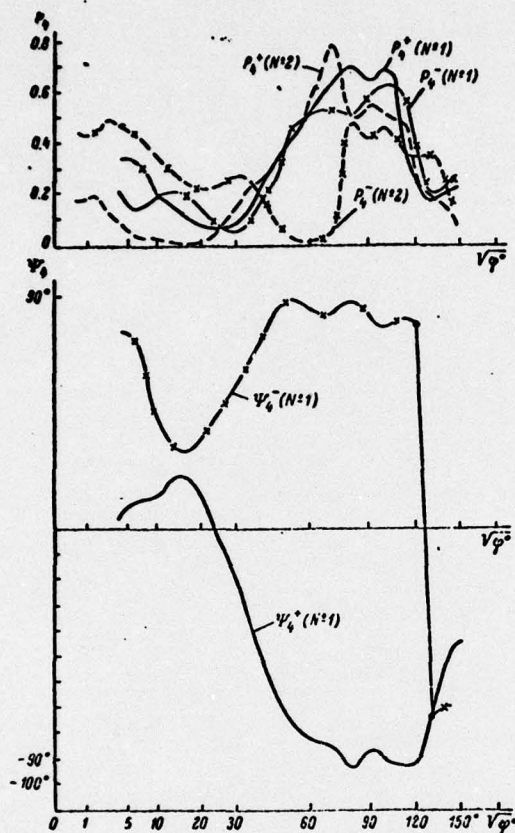sion is a dielectric with very low losses. The homogeneity of the scattered light

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Fig. 4. Degree of polarization P and polarization angle Ψ of scattered light from alternatively circularly polarized irradiating light beams.
For sample No. 2: from 0.5 to 10 and from 20 to 130° $\Psi_4^+ = \pi/2$; for $\phi = 15$ and 145° $\Psi_4^+ = 0$; from 0.5 to 50° $\Psi_4^- = 0$; from 70 to 145° $\Psi_4^- = \pi/2$.

$r_3(\phi)$ for sample No. 1 is higher. The angular shape of the polarization angle curve /1 makes it possible to assume a greater uniformity of the forms of the scattering centers, but with a marked deviation from sphericity. A greater uniformity with a smaller ρ characterizes sample No. 1.

<u>Scattering of horizontally and vertically polarized light beams</u> (Figs. 2, 3, 6). Concerning the $\tilde{f}_{12}$ component, the same may be said as for the $\tilde{f}_{13}$ and $\tilde{f}_{14}$ components. Its shape is somewhat similar to the shape for scattering centers in the form of spheres, but with a maximum smaller by 30-40%. The maximum for sample No. 1 is diffuse from 80 to 110°, and for sample No. 2, the maximum falls on $\phi = 100°$.

The greatest ellipticity is that of samples at a 90° scattering angle for a horizontally polarized beam. For sample No. 1, this ellipticity of q_2^- is very /146 pronounced. For scattering of the vertically polarized light beam, the ellipticity for both samples is insignificant over the entire range of scattering angles.
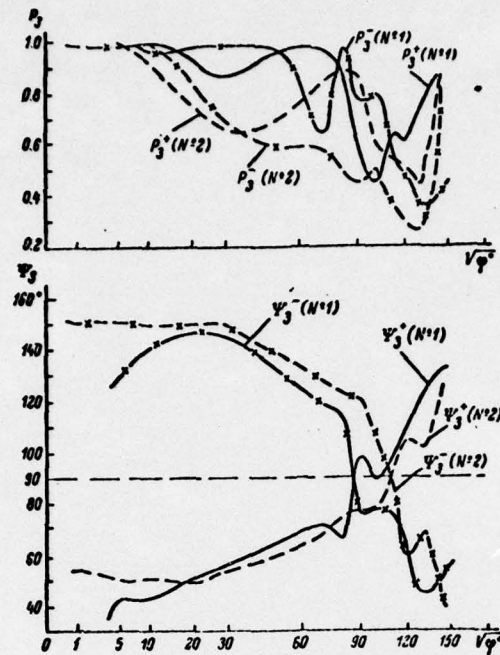
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Fig. 5. Degree of polarization P and polarization angle Ψ of scattering light from alternatively linearly polarized irradiating light beams at an angle of ±45°.

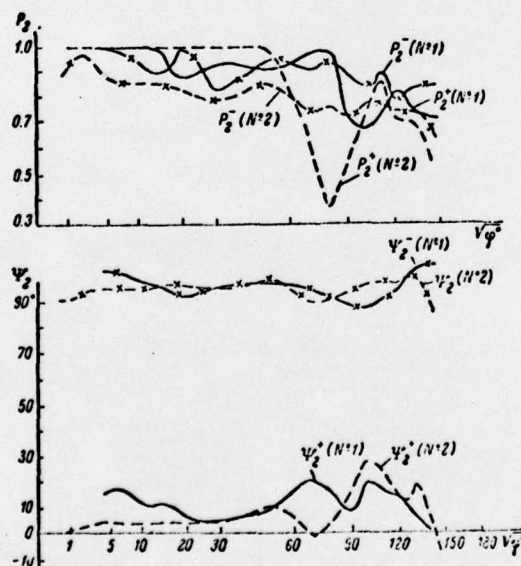**Fig. 6.** Degree of polarization P and polarization angle Ψ of scattered light from horizontally polarized (+) and vertically polarized (−) irradiating light beams.

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The dissimilarity in the behavior of q_2 indicates an appreciable anisotropy of the properties of the scattering centers. For sample No. 1, this anisotropy is higher.

The behavior of the r_2 curve once more confirms the view that the polydispersity of sample No. 2 is higher.

<u>Scattering of natural light</u> (Figs. 3, 7, 8). To within a constant factor, the f_{11} component of the scattering matrix gives the intensity of the scattered light when a volume of turbid medium is exposed to natural light. Figure 7 shows the scattering indicatrices for these two water samples. Many papers have discussed the analysis of the suspension using the form of the scattering indicatrix. It is always assumed that the suspension is spherical in shape. On the basis of the form of the scattering indicatrix, one can select the particle size distribution function. No data on the shape, optical properties, anisotropy of the scattering particles, and their orientation in space can be obtained from data on the indicatrix.
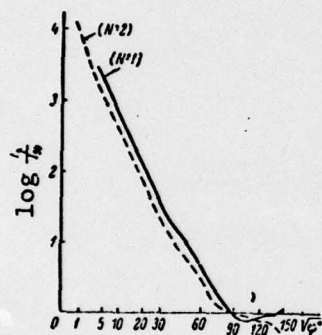

Fig. 7. Light scattering indicatrices for two samples of seawater, Nos. 1 and 2, with similar values of the scattering index.

In the scattering of natural light, there appears a slight ellipticity characteristic of particles of nonspherical shape, or inhomogeneity of the optical properties of the scattering centers. To within the experimental errors, the ellipticity may be considered the same for both samples. The degree of linear polarization P_* for sample No. 2 from 30 to 145° has a polarization angle of 90°, and at smaller angles, this angle is zero. Such behavior of the degree of polarization indicates a deviation from sphericity of the scattering centers that is smaller than for sample No. 1. The size spectrum for sample No. 2 is wider, as /147 indicated by lower values of the degree of homogeneity r_*.

The above-discussed angular dependences of the polarization characteristics of scattered light with similar values of the scattering index σ make it possible to detect a difference in the composition of the suspension in the samples studied.
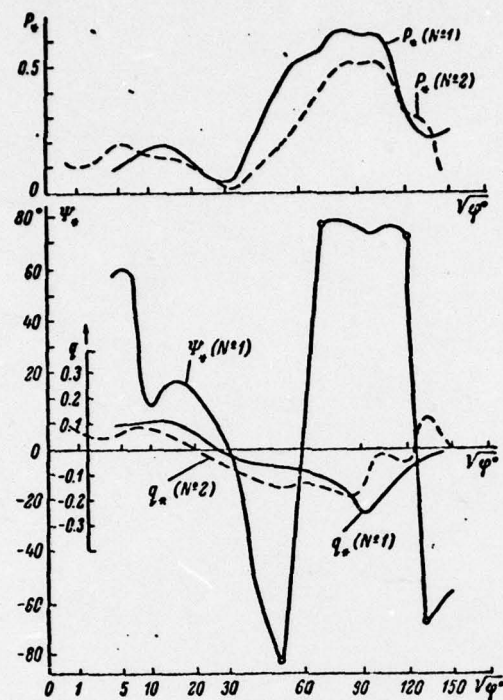
Fig. 8. Degree of polarization P and polarization angle Ψ of scattered light from a natural irradiating light beam.
For sample No. 2: for ϕ up to 30° $\Psi_* = 0$; for ϕ from 30 to 145° $\Psi_* = \pi/2$.

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3. Shifrin, K. S., Scattering of Light in a Turbid Medium (Rasseyaniye sveta v mutnoy srede), Moscow-Leningrad, 1951.